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RESEARCH FOUNDATION

CONTENTS

LOW TEMPERATURE DETECTORS FOR MILLIMETER RADIATION

1. SUMMARY OF SCOPE OF PROJECT

The purpose of the investigations undertaken under this project was the study of some fundamental physical problems associated with thermal detection of radiation. It is well known that for the detection of coherent radiation in the radio and microwave regions, "mixer" detectors using a local source of radiation of nearly the same frequency as the incident signal have the smallest minimum detectable power values for signal equal to noise. On the other hand, recent extensions of investigations to higher and higher radiation frequencies in the millimeter wavelength or in the far infrared region may result in some valid requirements for thermal detectors. To assess fully the value of such detecting systems it was considered that further work was necessary. Such work could be subdivided into theoretical and experimental approaches, and it was the purpose of this project to carry out such investigations.

Theoretically it is possible to calculate approximately the minimum detectable power for signal equal to noise for a thermal detector, and it is found in general that this minimum detectable power is diminished when the temperature is reduced and when the temperature dependency of the observed physical parameter is increased. In consequence one experimental study carried out under this project was a fundamental study of the possibility of the development of metallic bolometers which are partially superconducting at very low temperatures, such as phosphor-bronze, and which appear to offer many advantages. This study comprised the major scope of the work under this project.

2. PERIODS COVERED BY REPORTS

This project was in operation from April 1, 1951, to February 14, 1953. The theoretical and experimental researches carried out during the period April 1, 1951, to October 1, 1951 have already been reported in Status Report No. 1 dated October 15, 1951, and those for the period to September 30, 1952 in Technical Report No. 1 dated September 30, 1952. These were briefly summarized in Status Report No. 2 dated September 24, 1952. The experimental work carried out during the period September 30, 1952 to February 14, 1953 is detailed in the present report.

3. EXPERIMENTAL WORK (OUTLINE)

Five experimental runs at the temperature of liquid helium ($1^{o}K$ to $4.2^{o}K$) have been carried out in the period October 1, 1952 to February 14, 1953, with a total time of about 50 hours at these temperatures. The experiments concerned current noise measurements at low temperatures in partially superconducting Ta. Details of these experiments are given below in sections 4 and 5.

4. CURRENT NOISE IN Ta AT 4.2 ^{o}K

a. INTRODUCTION

As reported in Technical Report No. 1, our preliminary measurements on current noise in resistors of Ta when in the intermediate superconducting state showed that the noise power was considerably greater than that associated with Johnson noise. These measurements were carried out in the audiofrequency range at liquid helium temperatures, and the results could briefly be summarized as follows: If the ratio of the current noise power to the Johnson noise in the intermediate state is designated (n-1), than $(n-1)/i^2 \approx 15\ (ma)^{-2}$ where i is the dc biasing current through the resistor in milliamps.

In Technical Report No. 1 the suggestion was put forward that the observed current noise in the intermediate state in Ta might possibly be due to temperature fluctuations of the resistor as a whole, since such temperature fluctuations would result in fluctuations in resistance owing to the high value of the temperature coefficient of resistance in the intermediate state. This suggestion gained further emphasis in that no current noise was observed in the tantalum specimen when it was either in the normal or in the superconductive state, where, as is well known, the temperature coefficient of resistance is zero.

On the other hand, the experimental arrangements employed in these preliminary observations were such that it was not possible to assess even the order of magnitude of the thermal conductance of the tantalum wire itself to its surroundings, and in consequence it was not possible to compute the order of magnitude of the expected temperature fluctuations nor to draw any quantitative conclusions regarding our suggestion.

The question of whether the observed current noise in tantalum in the intermediate state was due to temperature fluctuations appears to us to be of extreme importance, in that, as we pointed out in Technical Report No. 1, if the observed current noise is indeed due to temperature fluctuations, than tantalum in the intermediate state would form a bolometer material of the highest possible ultimate signal-to-noise ratio. This question, therefore, was fundamental to the whole scope and purpose of the project. In order to make an experimental approach towards answering this question, a series of experiments were planned and executed in which the current noise in a tantalum wire freely mounted in an atmosphere of gaseous helium was observed as a function of frequency. Details of these experiments and the results and conclusions obtained from them are given below.

b. EXPERIMENTAL ARRANGEMENTS

A 548 cm length of tantalum wire of diameter 0.007 inch was wound in a bifilar manner on a mica former so constructed that the wire touched the mica only at four points per revolution of wire. By employing such a method of mounting the wire, one could be sure that the main path of thermal conductance between the wire and its surroundings would be at the interface between the wire and the helium gas in which the specimen was immersed. The conductance of heat between the wire and the mica former was computed to be negligible compared with the conductance through the metallic-gaseous interface.

The tantalum wire was placed in a chamber which could be either evacuated or filled to any desired pressure of helium gas, and this chamber in turn was mounted in a cryostat so that it could be maintained at a temperature of 4.2°K.

The noise voltage, with and without biasing current, across the specimen was observed over a narrow band-width of frequency at various frequencies in the audio-frequency range. The electronic arrangement used for this purpose has been described in detail in our Technical Report No. 1.

The tantalum wire used was supplied by the Fansteel Metallurgical Corporation and was of stated purity 99.9%.

Since the transition temperature of tantalum is approximately 4.4°K, it was necessary to apply an external transverse magnetic field of about 60 gauss to bring the tantalum into the intermediate state at 4.2°K, which temperature is most conveniently obtained with liquid helium boiling under atmospheric pressure.

Details of the methods of calibrating the electronic amplifying system, etc., have been given in Technical Report No. 1.

c. MEASUREMENTS OF THE TEMPERATURE COEFFICIENT OF RESISTANCE OF THE TANTALUM SPECIMEN AND MEASUREMENTS OF THE THERMAL CONDUCTANCE

In order to compute the expected magnitude of the temperature fluctuations in the specimen, it was necessary to find the temperature coefficient of resistance of the tantalum under the conditions of our experiments and to measure simultaneously the thermal conductance between the wire and its surroundings.

The temperature coefficient of resistance, α, is given by

$$\alpha = \frac{1}{R}\left(\frac{\partial R}{\partial H}\right)_T \cdot \left(\frac{\partial H}{\partial T}\right)_R \qquad (1)$$

where $(\partial H/\partial T)_R$ is the slope of the magnetic threshold curve of tantalum, as measured by resistance measurements taking the half value of the normal resistance as the point of transition. This term $(\partial H/\partial T)_R$ is well known from the measurements of Daunt and Mendelssohn[1] and is equal to -325 gauss per degree at 4.2°K. Our present measurements on tantalum confirm this evaluation. The term $(\partial R/\partial H)_T$ was measured directly by observing the dc resistance of the specimen as a function of the applied magnetic field, H. The dc resistance, R, was measured using a Rubicon potentiometer, catalog number 2732, using the circuit illustrated in Fig. 1. The results of this measurement are shown in Fig. 2, which plots R versus H for a constant temperature of measurement of 4.2°K. The slope of the curve, $(\partial R/\partial H)_T$ at the half value of the normal resistance is somewhat difficult to estimate with any accuracy because the transition probably does not proceed smoothly but in jumps, so that the R versus H curve may have a steplike

1. J. G. Daunt and K. Mendelssohn, Proc. Roy. Soc. A. **160**, 127 (1937).

character with very steep slopes between the steps (cf. Andrews'[2] results on NbN); and, as noted below, the potentiometer could never be accurately zeroed, owing to the fluctuations occurring in the resistance. From the smoothed curve of Fig. 2, using also equation (1), it is estimated that the value of the temperature coefficient of resistance, α , lies between the limits:

$$80 \text{ per } ^\circ K < \alpha < 120 \text{ per } ^\circ K \tag{2}$$

In our subsequent computations we will put $\alpha = 100$ per $^{\circ}$K. Instantaneously, however, if the transition is a steplike process, values of α greater than 120 per $^{\circ}$K could be expected.

The value of the thermal conductance, G, between the wire and its surroundings was determined in the manner reported in detail in Technical Report No. 1, the method consisting of passing a dc biasing current through the wire and measuring the change in resistance produced thereby. From this data, the value of the resistance, R, as a function of the input power, P, can be computed. Fig. 3 shows the results obtained for R versus P at 4.2°K in a magnetic field of 60.3 gauss. The value of G can be obtained from such curves as that shown in Fig. 3 and from a knowledge of the value of the temperature coefficient of resistance, α , by means of the following equation:

$$G = \frac{dP}{dT} = R\alpha / \left(\frac{dR}{dP}\right) \tag{3}$$

The value of (dR/dP) α = 2.8×10^5 ohms/watt taken from Fig. 3, together with the value of α = 100 per $^{\circ}$K, enables the G value for a helium gas pressure equal to 74.4 cm Hg to be computed. It is:

$$G = 3.6 \times 10^{-4} \text{ watt per degree} \tag{4}$$

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2. D. H. Andrews, Phys. Soc. (London) Camb. Conference Report, p. 56 (1947).

The value of $(dR/dP) = 2.8 \times 10^5$ ohms per watt taken from Fig. 3 is unfortunately not very accurate, owing to the curvature of the R versus P curve near the origin of P. Some allowance must be made, therefore, for this possible inaccuracy, and it may be that the value of G is somewhat higher than that given in equation (4).

Attempts were made to measure the value of G at lower helium gas pressures, namely at 11 cm Hg and at 1.3 cm Hg, but it was impossible to obtain accurate data because large fluctuations appeared in the dc resistance of the specimen. It was somewhat a surprise to observe these fluctuations when measuring the resistance of the specimen with a potentiometer, particularly as they appeared to represent resistance changes as large as 5% of the total resistance. Details of these fluctuational observations are given below in section 4(d).

d. THE NOISE MEASUREMENTS

The noise measurements were carried out using a narrowband amplifier and recorder which could be tuned to any desired frequency in the audiofrequency range. No details of the technique need be mentioned here, since they have been described in Technical Report No. 1.

In order to present the results, it is convenient to use the parameter, n, given by

$$n = \frac{\text{total noise power in resistor}}{\text{Johnson noise power in resistor}} = \frac{\text{current noise power}}{\text{Johnson noise power}} + 1 \qquad (5)$$

One readily notes that $(n-1)/i^2 = \beta$, where i is the dc biasing current and where

$$(n-1) = \Delta v^2 / 4kT_s R_s \Delta f \cdot \Gamma \qquad (6)$$

From our observed data on the Ta specimen in the intermediate state, the noise power was found to be accurately proportional to i^2, and so we have computed the values of $(n-1)/i^2$ at various frequencies of observation and at three different pressures of the helium gas surrounding the specimen. The results are recorded in Table I.

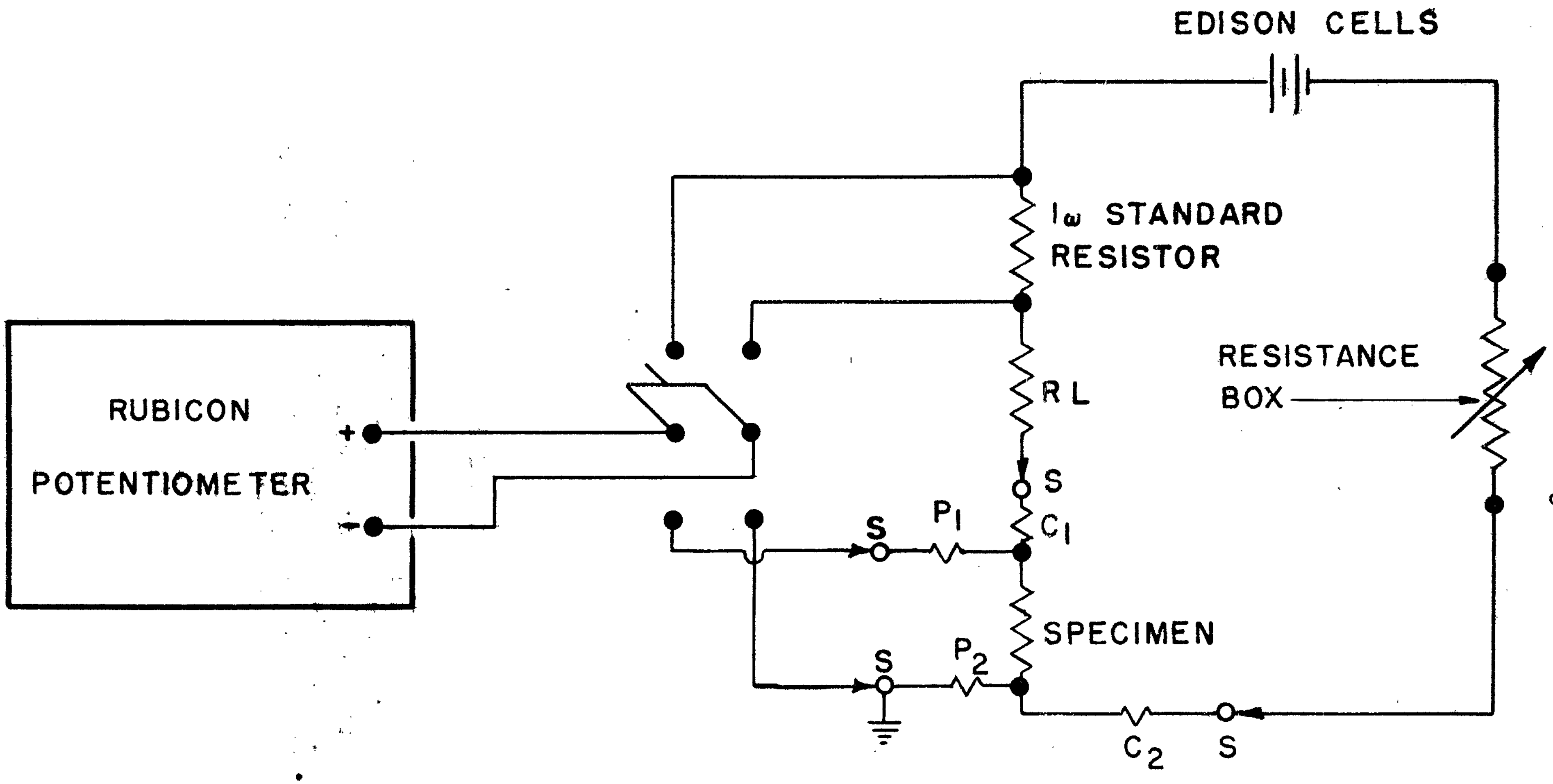

FIG. 1 CIRCUIT FOR MEASURING ELECTRICAL RESISTANCE OF SPECIMEN

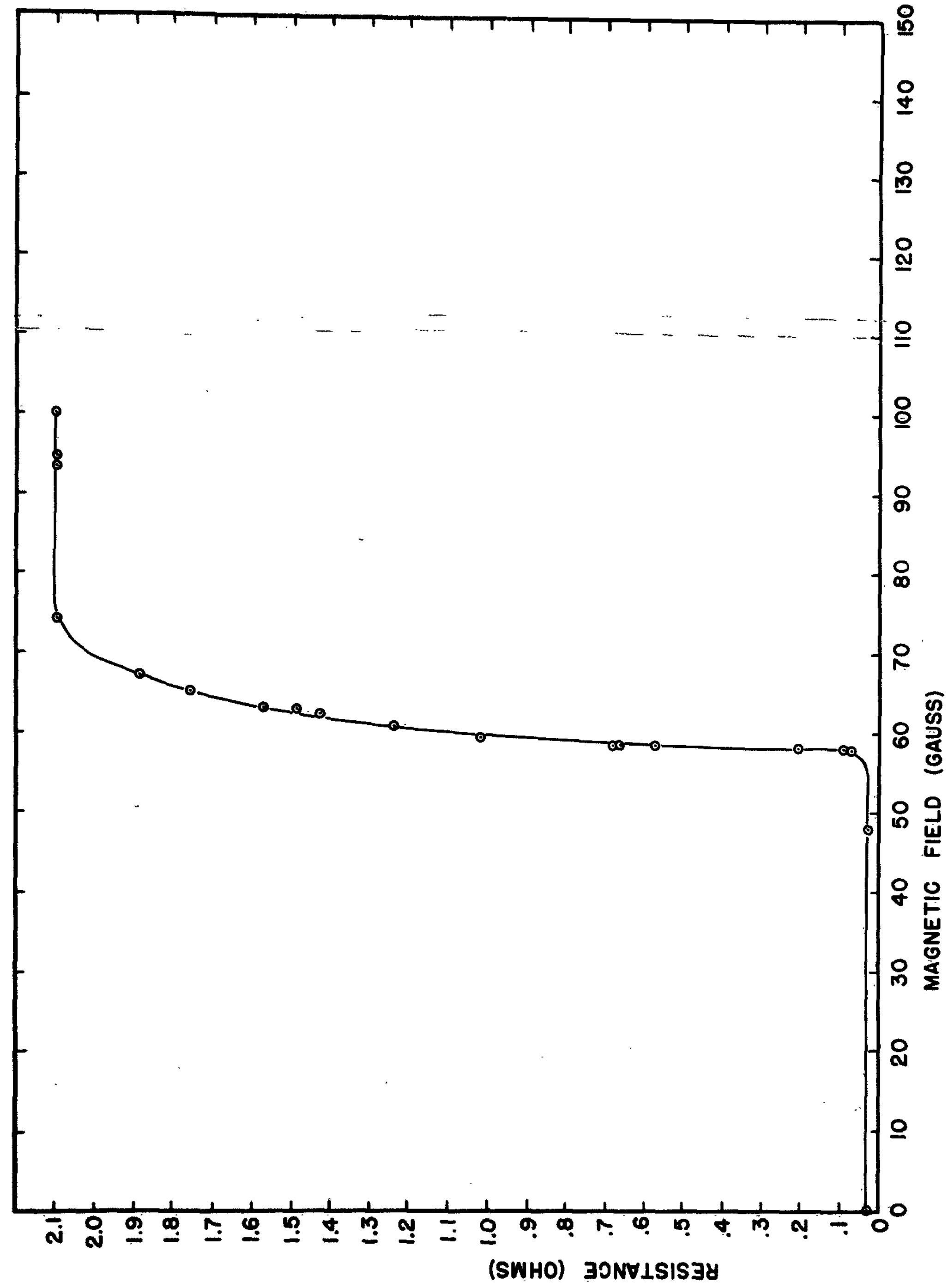
RESISTANCE (OHMS)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
MAGNETIC FIELD (GAUSS)

FIG. 2

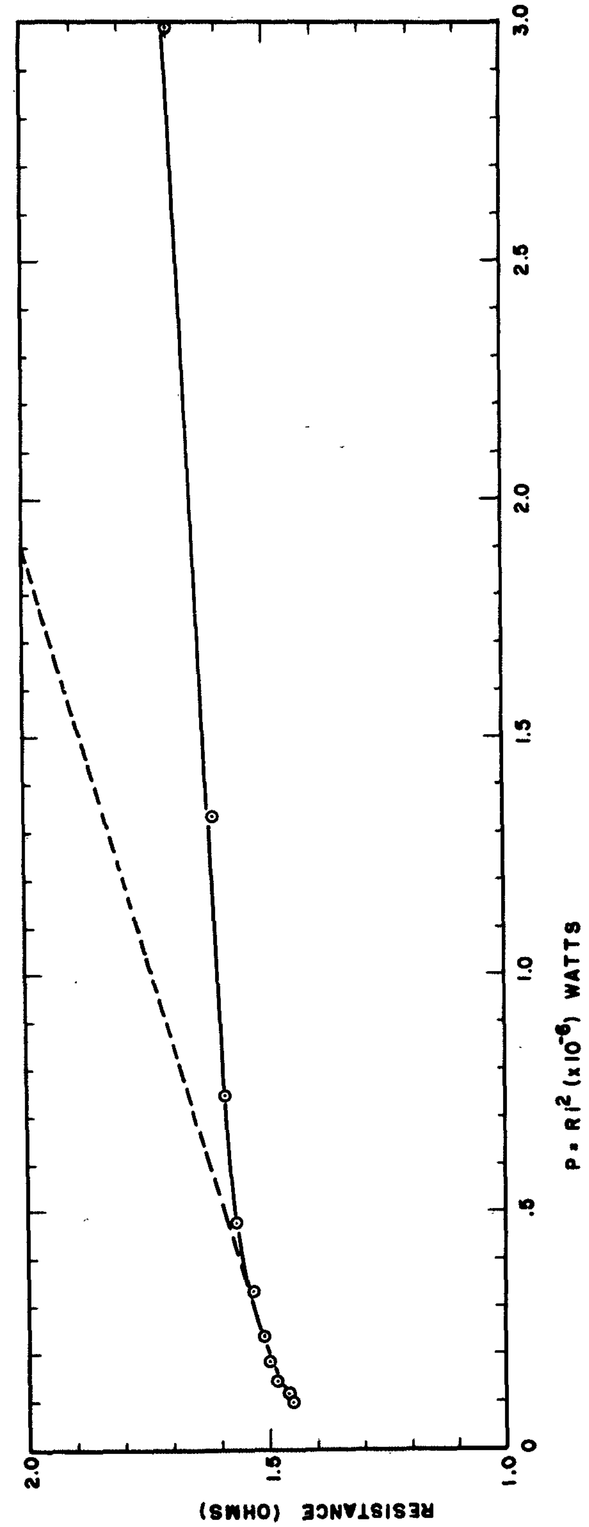

FIG. 3

It will be noted first that, with the exception of doubtful evaluation at $f = 500$ and $p = 11$ cm Hg, the value of β is of order of magnitude 10×10^6 per amp, a value in fair agreement with that reported previously by us in Technical Report No. 1. Secondly, it can be seen that the value of β, and hence the current noise power, increases steadily as the gas pressure around the specimen is diminished. This feature is reproduced also in the dc noise measurements as shown in column 3, Table II. Finally, owing to the limits of error of evaluating the noise, it is not possible to conclude anything regarding the frequency dependence of the current noise.

The results of measurement of the fluctuations using the potentiometer, the galvanometer of which had a period of two seconds and a computed bandwidth of 2 sec^{-1}, are given in Table II. The assessment of the mean square voltage fluctuation from observation of the galvanometer needle was necessarily somewhat crude and the numbers given in column 3 of Table II therefore represent an order of magnitude only. In view of this, it is not possible to decide whether the mean square fluctuational voltage $\overline{\Delta V^2}$ is accurately proportional to the square of the dc biasing current, i_{dc}, as one would expect on theoretical grounds. The computed values of $(n-1)/i^2$ given in column 5, however, were obtained by assuming a linear relationship between $\overline{\Delta V^2}$ and $(i_{dc})^2$. It is to be reported that the dc noise power per unit biasing current decreased with increasing current, due to the fact that the increase of current shifted the specimen nearer to the normal state.

As reported previously in Technical Report No. 1, these new noise measurements showed no evidence of current noise either in the audiofrequency range or using the dc potentiometer when the specimen was in the completely normal state or in the completely superconducting state.

TABLE I.

AC (AUDIOFREQUENCY) MEASUREMENT OF THE CURRENT NOISE POWER OF THE Ta SPECIMEN IN THE INTERMELIATE STATE AT A CONSTANT MAGNETIC FIELD, H = 56.6 GAUSS AND AT A CONSTANT TEMPERATURE OF 4.2°K.

(Bandwidth of measurement was 1.0% of the frequency of observation.)

Frequency cycles/sec	Pressure of helium gas around specimen, cm Hg	$\beta = (n-1)/i^2$ (amp) $^{-2}$
300	74.4	4.05×10^6
500	74.4	7.65×10^6
750	74.4	5.64×10^6
300	11	7.35×10^6
500	11	(40×10^6)
750	11	8.85×10^6
300	1.3	13.2×10^6
500	1.3	9.68×10^6
750	1.3	6.9×10^6

TABLE II.

CURRENT NOISE (QUASI-dc) OBSERVED, USING THE POTENTIOMETER, IN THE Ta SPECIMEN IN THE INTERMEDIATE STATE AT A CONSTANT TEMPERATURE OF 4.2°K

R ohms	Pressure of helium gas around specimen, cm Hg	$\left(\overline{\Delta V^2}\right)^{1/2}$ μV	i_{dc} ma	$\beta = (n-1)/i^2$ $(amp)^{-2}$
1.753	76	19	2.715	5.94×10^{16}
0.68	11	9	0.256	3.03×10^{18}
1.12	11	30	2.510	2.75×10^{17}
1.27	11	24.8	4.558	5.03×10^{16}
1.89	11	35	9.208	1.64×10^{16}
0.405	1.0	28	0.256	6.53×10^{19}
?	1.0	117	2.782	3.91×10^{18}
1.38	1.0	125	3.925	1.59×10^{18}

e. DISCUSSION

If it is assumed that the observed current noise, evident only when the specimen is in the intermediate state, is due to temperature fluctuations of the specimen as a whole, then it is possible to correlate the various parameters concerned as follows, since $\omega C \gg G$:

$$\frac{\beta}{RT} = \frac{1}{RT}\frac{(m-1)}{i^2} = \frac{\alpha^2 G}{\omega^2 C^2} \tag{7}$$

The known values of these parameters are as follows:

α = 100 per ^{o}K

G = 3.6×10^{-4} watt/deg.

C = 5×10^{-4} joule/deg.

The value of C, the heat capacity of the specimen, was computed from its known mass and from the known specific heat of tantalum as measured by Keesom and Desirant.[3] In Table III we give the computed values of β/RT and of $\alpha^2 G/\omega^2 C^2$. It will be seen from this table that the equality expected between these two terms as shown in equation (7) is not valid. Instead it is evident that for the ac measurements the term $\alpha^2 G/\omega^2 C^2$ is approximately 10^6 times too small and that in the dc case the term $\alpha^2 G/\omega^2 C^2$ is approximately 4×10^9 times too small.

From these comparisons, if the α value of 100 per ^{o}K can be assumed correct, then it would appear that the observed current noise is not due to temperature fluctuations of the specimen as a whole, since these fluctuations would produce noise fluctuations very much smaller than those which we observed. On the other hand both the ac measurements (see Table I) and particularly the dc measurements (see Table II) indicate clearly that the observed current noise is a marked function of

3. W. H. Keesom and M. Desirant, Leiden Comm. No. 257b.

the pressure of the helium gas surrounding the specimen, the noise power increasing as the pressure is reduced. This can only be interpreted as indicating that the observed current noise power is dependent on the thermal conductance between the specimen and its surroundings and increases as the thermal conductance is diminshed. This interesting result tends to make one conclude that indeed some kind of temperature or energy fluctuations provide the basic mechanism for the current noise, but that the detailed interpretation may be arrived at only by: (1) assuming that the value of $\alpha = 100$ per ^{o}K used here is incorrect and that, because of the steplike character of the transition, values of α some hundred times larger than this occur, or (2) that the heat capacity, C, to be used in equation (7) is not the total heat capacity of the body, but instead the current noise is due to energy or temperature fluctuations in a subassembly the nature of which is not yet determined.

All that one can say at this stage regarding such a subassembly is that it is not represented by the heat capacity of the specimen as a whole. It would be entirely speculative to consider possible subassemblies, as for example the electron system or the possible domain structure in the intermediate state, but it is clear that further experimental work is necessary in order to discover the nature of the assembly.

In considering the discrepancies evidenced in Table III between the observed current noise power and the computed noise power expected on the basis of temperature fluctuations, there are a few possibilities of interpretation, which we now discuss.

It is clear that the term $\alpha^2 q/\omega^2 C^2$ shown in column 3 of Table III, which appears to be too small, could indeed be too small owing to the possibility that either the measurements of α and hence of G yielded too small values or that the term C, computed on the basis of the heat capacity of the whole wire, may be too large.

The first alternative, that our measurements of yielded values which are too small, can in principle be checked by an entirely different experimental approach; and our preliminary experiments in this direction, which regrettably have not been carried to conclusive results owing to the imminent termination of the project, are described in Section 5.

The second alternative, that the estimated value of C based on the heat capacity of the specimen as a whole is too large, presents the problem of interpretation of the nature of the assembly that undergoes fluctuation. In discussing this, mention should be made of some preliminary measurements of Webber [4], who also measured the resistance of tantalum through the transitional region, and who likewise found fluctuations in the resistance of the specimen as measured by a dc potentiometer. He reported that for a specimen for which the ratio of the normal resistance at 4.4°K to the resistance at 2.73°K, R_{44}/R_{273}, was equal to 0.15, fluctuations of magnitude of about 5% of the total resistance were observed in the resistance of the specimen in the transition region at zero magnetic field. For another specimen for which $R_{44}/R_{273} = 0.07$, which had been annealed, he observed only approximately 1.5% resistance fluctuation. These very brief results indicated that perhaps the assembly or mechanism responsible for the fluctuations in tantalum is intimately connected with the impurity content in the metal, and is such that for decreasing impurity content the current noise decreases. It is to be noted that for our specimen the value of $R_{4.2}/R_{273}$ was 0.06, which would indicate, judging by Webber's results, that for our specimen the current noise may also be associated with the impurity content of the metal.

In this connection it may be worth recalling the so-called "overshoot phenomena" reported in some detail by Silsbee [5], which revealed peculiar jumps in the resistance of tin and tantalum wires as they were carried through the superconducting transition by changing the temperature of the liquid helium bath in which they were

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4. R. T. Webber, Physical Review, <u>72</u>, 1241 (1947).

5. F. B. Silsbee, R. B. Scott, and F. G. Brickwedde, J. Res. NBS <u>18</u>, 295 (1937).

immersed. The detailed experiments of Misener[6] on the overshoot phenomena showed that as the sample of superconducting wire was made sufficiently pure the phenomena were suppressed. For example, he reported marked unsteadiness in the transition, as much as 50% of the total resistance, in a tantalum wire for which $R_{4.2}/R_{273} = 0.28$, whereas for a much purer sample of the same material, for which $R_{4.2}/R_{273} = 0.010$, he observed no unsteadiness or fluctuation.

If indeed the fluctuational phenomena revealed by our measurements of the current noise in tantalum are due to excessive impurity content in the material, it must be concluded that they are of a secondary character and would be absent for specimens of sufficiently high purity. In order to test this conclusion experimentally it would be necessary to make observations of the current noise similar to those reported in this paper, using specimens of metal wires, as for example tin or lead, which can readily be obtained in a state of very high purity. Such experiments had been planned by us but could not be completed owing to the termination of the project.

5. THE BRIDGE MEASUREMENTS

a. INTRODUCTION

The conclusions reached from the current noise measurements of tantalum in the intermediate state, outlined in Section 4e, are dependent critically on the numerical evaluation of the term $\alpha^2 G/\omega^2 C^2$, where α is the temperature coefficient of resistance, G is the thermal conductance to the surroundings, and C is the heat capacity of the system. Moreover one notes from equation (3) that the computed value of G is proportional to α. In consequence the quantity of interest to us is the term α^3/C^2. It was thought of importance, therefore, to use another experimental approach for the evaluation of these characteristic

6. A. D. Misener, Proc. Camb. Phil. Soc. 34, 465 (1938).

constants. The measurements to be described in this section were carried out since it could be shown that they either would reveal an exact evaluation of this term, or alternatively would reveal at least an upper limit for its numerical magnitude.

The experiments consisted in putting the same tantalum specimen used in the experiments described in Section 4 into a Wheatstone Bridge circuit as shown in Fig. 4. The bridge was connected in such a manner that a small direct current, i_{dc}, of magnitude 2.14 ma, would flow through the specimen while an alternating current, i_{ac}, also passed through the specimen.

The principle of the experiment relied on the fact that, as the specimen has a finite temperature coefficient of resistance, the alternating current will produce ac resistance changes at the frequency of the first overtone of the ac current. The detecting system used in the bridge then could measure the overtones, and consequently simultaneous evaluation could be made of the temperature coefficient of resistance and of the heat capacity of the specimen. Suppose that the ac current through the specimen is given by:

$$i_{ac} = i_0 \sin \omega t + a i_0 \sin 2\omega t + b i_0 \sin 3\omega t + \dots \qquad (8)$$

where the terms a, b, etc. give an indication of the value of the overtones inescapably present in the signal applied to the bridge.

It can then be readily shown that if $B < \Delta R$ the value of the amplitude of the output voltage at the fundamental frequency $\omega/2\pi$ is given by:

$$f \cdot V_\omega = i_0(\Delta R + \tfrac{3}{4}B) \sin \omega t + a\, i_{dc}\, B \cos \omega t \qquad (9)$$

where f is the bridge factor, ΔR is the amount of resistance by which the specimen is off balance on a dc measurement, and the term B is given by:

$$B = \frac{\alpha R^2 i_0^2}{2\omega C} \quad \text{ohms} \qquad (10)$$

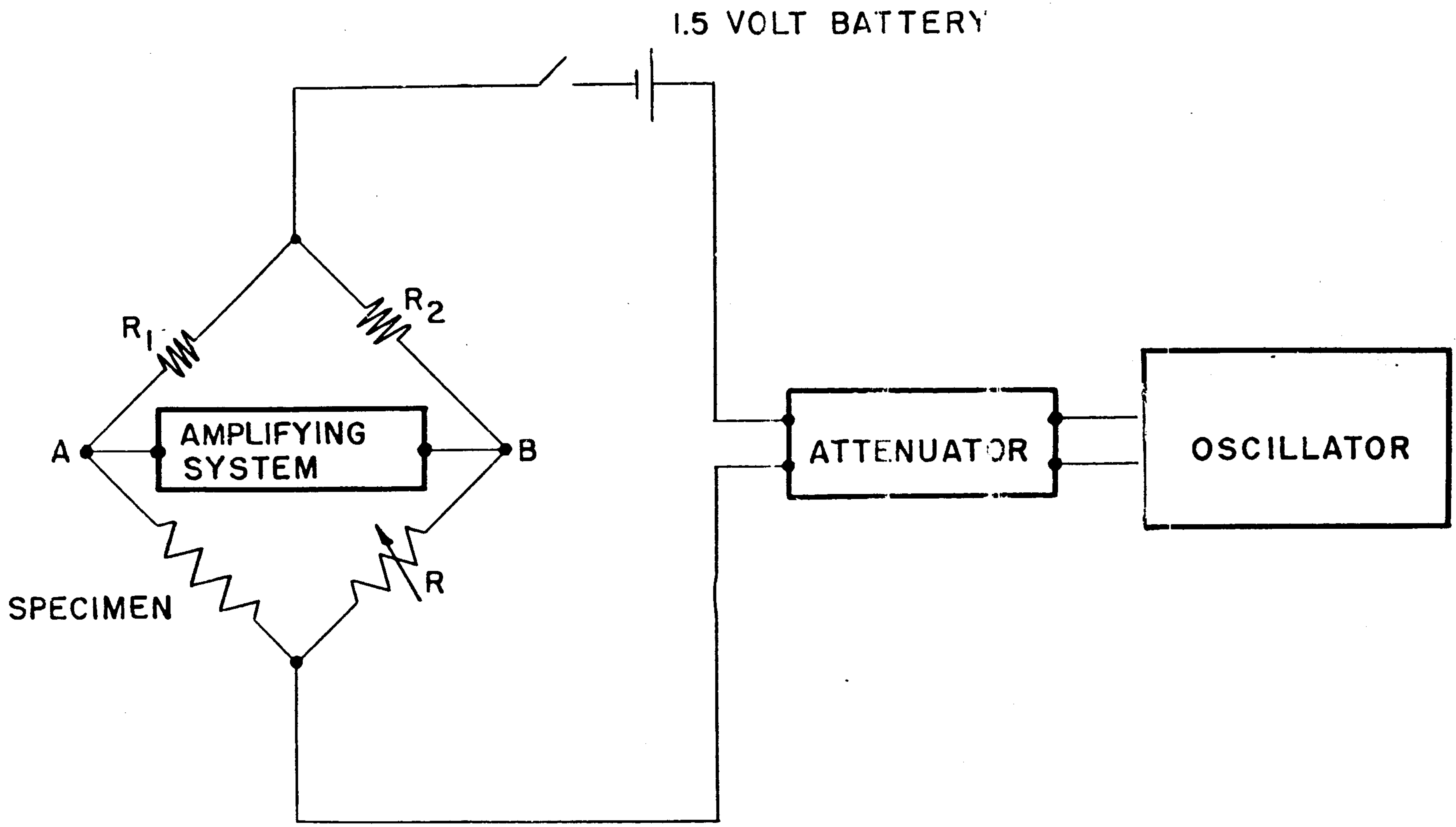


FIG. 4 SCHEMATIC CIRCUIT USED FOR BRIDGE MEASUREMENTS

The output voltage $V_{2\omega}$ from the bridge at the first overtone, $2\omega/2\pi$, is given by:

$$\text{f}\, V_{2\omega} = a i_o (\Delta R + \tfrac{3}{2} B) \sin 2\omega t - \tfrac{1}{2} i_{dc} B \cos 2\omega t \qquad (11)$$

In principle, therefore, by measurement of the output voltages from the bridge at the fundamental frequency and at succeeding overtones, it is possible to evaluate the term B and hence gain a knowledge of the parameters of interest. Such an operation would require also, of course, a direct measurement of the harmonic content, i.e. of a, b, etc., of the signal impressed on the bridge.

b. THE MEASUREMENTS

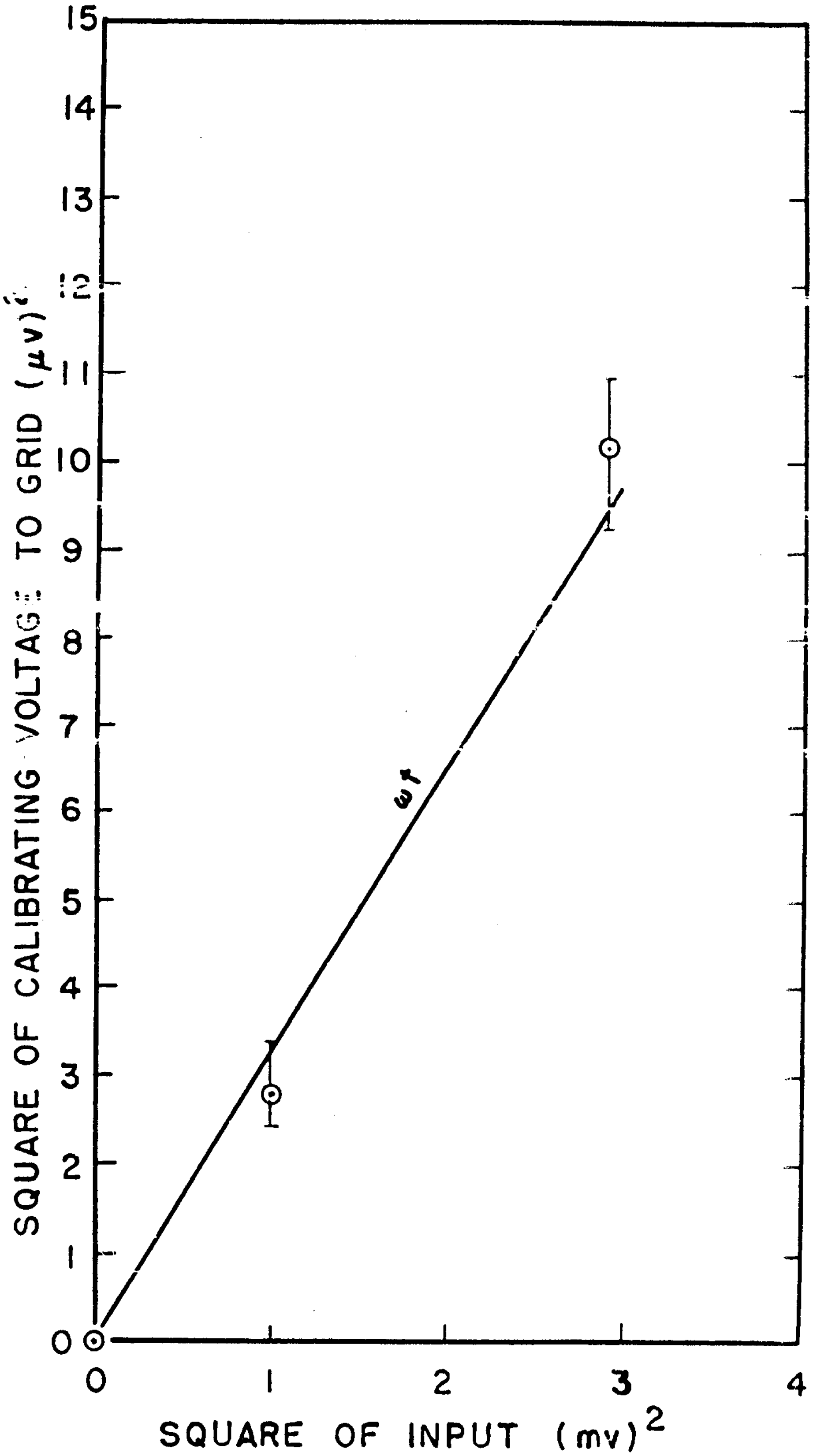
A bridge was set up as diagrammatically shown in Fig. 4, and the tantalum specimen was maintained in a cryostat in such a way that it could be held either in the intermediate state or in the normal state.

The detecting system for the bridge was identically the same electronic system as employed for the current noise measurements and is described in detail in Technical Report No. 1.

Before switching on the ac circuit the bridge was balanced as well as possible using a dc galvanometer as detector. Then the ac signal was switched on and the output was measured as a function of the ac current, i_o, at the fundamental frequency and at the first three overtones.

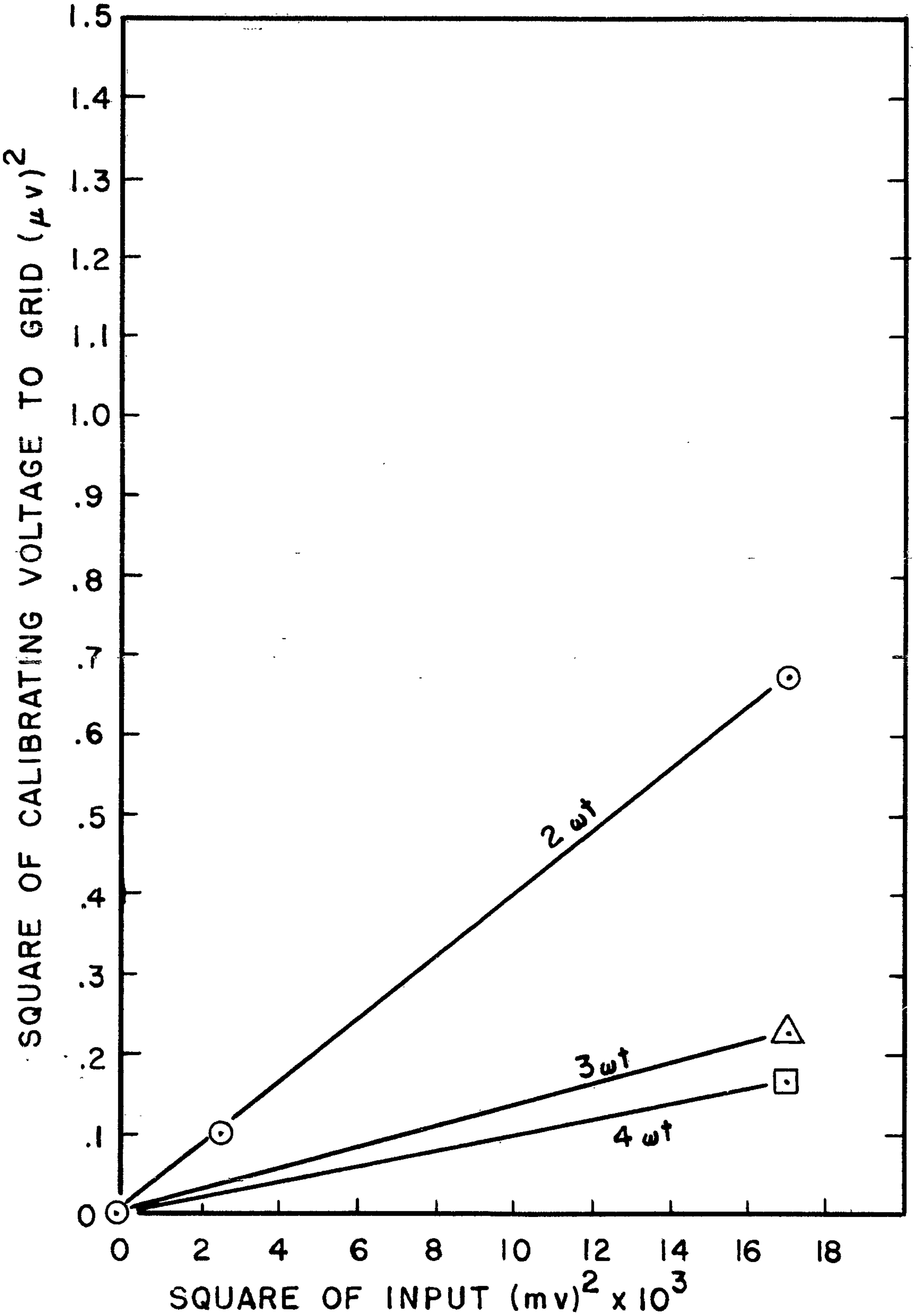
The results obtained for the measurements when the tantalum specimen was in the normal state in a magnetic field of 154 gauss at a temperature of 4.2°K are shown in Figs. 5A and 5B.

The results obtained when the specimen was in the intermediate state in a magnetic field of 60.3 gauss and at a temperature of 4.2°K are shown in Figs. 6A and 6B. It will be noted first that, as would be expected, the square of the output voltage from the bridge is linearly proportional to the square of the input ac voltage to the bridge.



NORMAL STATE

FIG. 5 A



NORMAL STATE

FIG. 5 B

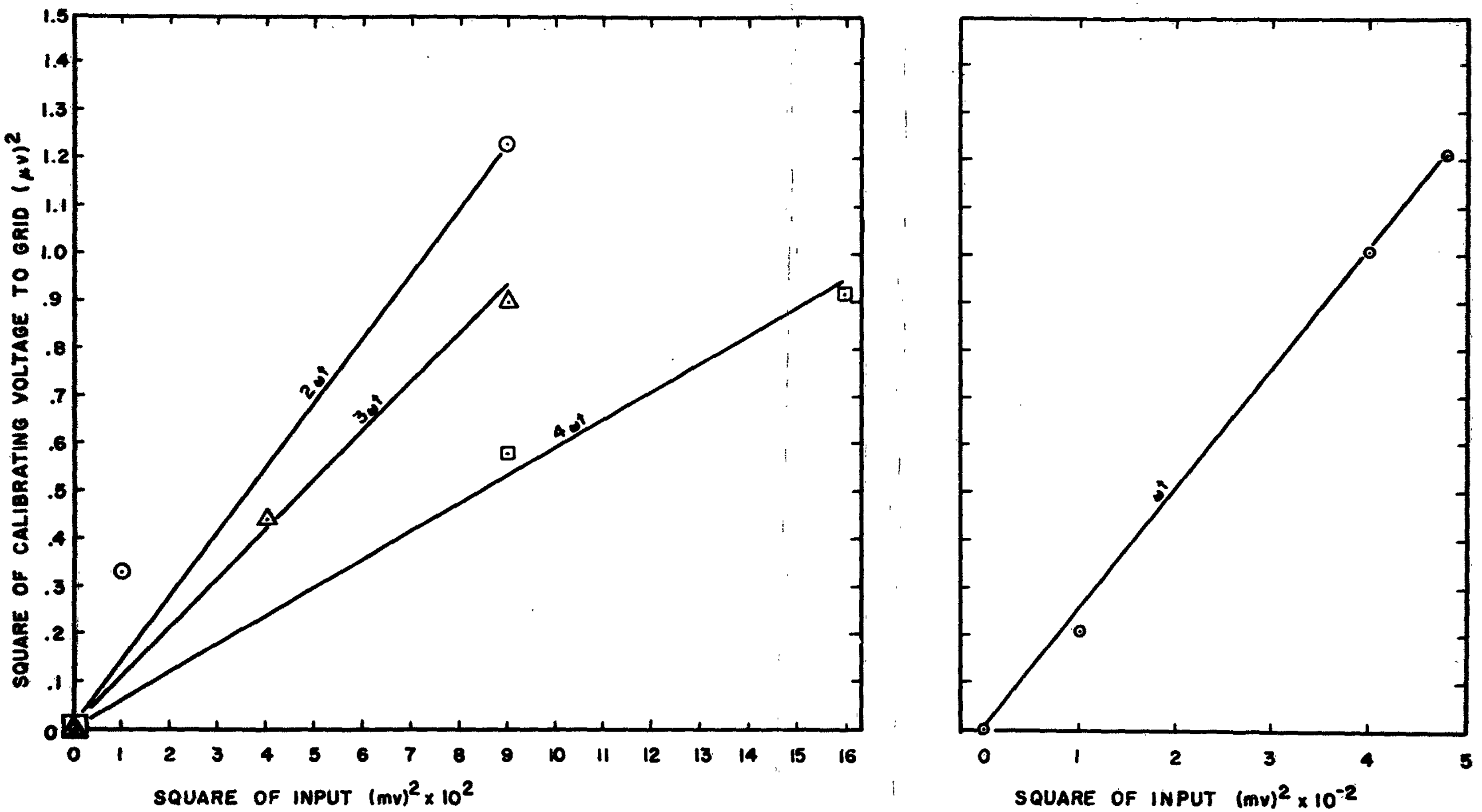


FIG 6 INTERMEDIATE STATE

As will be shown in section 5C, the parameters of interest are the ratios, r_1, r_2, r_3 ..., of the output voltage at each overtone to the output voltage at the fundamental frequency, both per unit input voltage. All our observed data, giving the slopes of the curves illustrated in Figs. 5A and 5B and 6A and 6B, and giving these ratios of interest, are presented in Table IV.

It will be seen from Table IV that these ratios, r_1, r_2, r_3, ..., at all the overtones measured are, within experimental error, independent of whether the specimen was in the normal or intermediate state. This result, as we shall discuss in Section 5c, indicates that the factor preponderantly influencing the ac outputs at the first three overtones is the harmonic content of the signal impressed on the bridge rather than effects due to the large temperature coefficient of resistance in the intermediate state.

It was of importance, therefore, to measure this harmonic content of the signal impressed on the bridge, an observation which was made using an oscilloscope to measure the output from a narrow-band amplifier connected to the ac source.

The results of these observations are compiled in Table V, in the last column of which are tabulated the values of the terms a, b, etc., defined by equation (8).

c. OBSERVATIONS

The measurements reported in the above section showed that

$$a = 8.6 \times 10^{-3}$$

$$\Delta R = 2.72 \times 10^{-2} \text{ ohms (for intermediate state)}$$

$$\Delta R = 1 \times 10^{-2} \text{ ohms (for normal state)}$$

$$i_{dc} = 2.14 \text{ ma (for both normal and intermediate state)}$$

i_0 (maximum value used) = 80 μa (for intermediate state)

i_0 (maximum value used) = 265 μa (for normal state)

TABLE IV.

RESULTS OBTAINED FOR THE RATIOS, $r_1, r_2, \ldots,$ OF THE OUTPUT VOLTAGE FROM BRIDGE AT THE FIRST, SECOND, ...OVERTONE TO THE OUTPUT AT THE FUNDAMENTAL FOR A FIXED INPUT VOLTAGE

The 2nd and 3rd columns give data obtained from Figs. 5A, 5B, 6A, 6B.

Frequency, cps	Slope of $(V_{out})^2/(V_{in})^2$ $(\mu v)^2/(mv)^2$		r values $r_i = V_{out}/V_{in}$	
	normal state	intermediate state	normal state	intermediate state
250	3.54	29	—	—
500	4×10^{-4}	3.1×10^{-3}	10.6×10^{-3}	10.3×10^{-3}
750	1.36×10^{-4}	9.76×10^{-4}	6.2×10^{-3}	5.8×10^{-3}
1000	1.06×10^{-4}	5.37×10^{-4}	5.5×10^{-3}	4.3×10^{-3}

TABLE V.

HARMONICS FROM OSCILLATOR

Frequency, cps	Overtone output in volts / Fundamental output in volts
250	--
500	a = 8.6×10^{-3}
750	b = 3.9×10^{-3}
1000	c = 3.0×10^{-3}

$R = 1$ ohm (for intermediate state)

$R = 2$ ohms (for normal state)

$f \approx 1$ (Bridge factor)

In addition to the above data we also can make some computations regarding the value of B from the data reported in Section 4c. If one assumes that the heat capacity, C, is that of the tantalum specimen taken as a whole, then

$$C = 5 \times 10^{-4} \quad \text{joules per } {}^{\circ}K$$

Using this value of C and choosing, for example, the first overtone frequency, namely 500 cycles per second, and using the values of $\alpha = 100$ per $^{\circ}K$, $G \approx 4 \times 10^{-4}$ watts per $^{\circ}K$, $i_0 = 10^{-4}$ amperes, $R = 1$, (which values are the same as those quoted above) one notes that

$$B = 4 \times 10^{-7} \text{ ohm.}$$

It was noted in the discussion of the current noise in tantalum, given in Section 4e, that in order for the ac results to be explained by temperature fluctuations of the specimen as a whole, the value of α/C should be increased by a factor of approximately 10^3. This would mean, therefore, that the value of B, as for example at 500 cycles per second, would have to be larger by approximately the same factor.

Even if one accepts values of B of the order of magnitude of 4×10^{-4} ohm, this value remains negligibly small compared with the value of ΔR. It is therefore possible to make considerable simplifications of equations (9) and (11), giving the amplitude of the output voltage from the bridge at the fundamental and at the first overtone. These simplifications, noting the small value of a given in Table V, together with the value of the parameters of interest listed at the head of this section, can be further extended and yield the following results:

$$f \cdot V_\omega = i_0 \Delta R \sin \omega t$$

$$V_{2\omega} = a i_0 \Delta R \left\{ \sin 2\omega t - \frac{\gamma B}{\Delta R} \cos 2\omega t \right\}$$

where $\gamma = i_{dc}/2 a i_0 \approx 10^3$

Combining these two equations, when $B \ll \Delta R$, we obtain:

$$r_1 = \frac{|V_{2\omega}|}{|V_\omega|} \approx a\left\{1 + 5\times 10^5 \left(\frac{B}{\Delta R}\right)^2\right\} \tag{12}$$

Equation (12) shows that r_1 is different from the harmonic content factor, a, by only a small factor given by the second term on the right hand side. Assuming the results of measurement of r_1 (see Table V) are accurate only to 10%, we note from the apparent agreement between the values of r_1 for the normal and intermediate state that

$$5\times 10^5 \left(\frac{B}{\Delta R}\right)^2 \leq 0.1 \tag{13}$$

Putting in the value ΔR = 1x 10^{-2} ohm, we get

$$B \leq 4.5\times 10^{-5} \text{ ohm}$$

Or, from equation (10), using the value C = 5 x 10^{-4} joules/$^{\circ}$K,

$$\alpha \leq 10^4 \text{ per degree K}$$

This result is unfortunately such that it does not allow a conclusive deduction regarding the temperature fluctuations to be made; for, as we saw in Section 4c, if $\alpha = 10^4$ instead of the assumed value of 10^2 per $^{\circ}$K, then temperature fluctuations of the specimen as a whole are sufficient to explain our results, at least in the audiofrequency range of observations. Further bridge measurements are required, therefore, before a definitive conclusion can be reached.

6. SUMMARY OF CONCLUSIONS OBTAINED; NOTES FOR DESIRABLE FUTURE ACTION

We give below a summary of conclusions obtained not only from experiments reported here, but also from the experiments reported in Technical Report No. 1.

No evidence of current noise greater than 4.5 db above Johnson noise power was observed in a resistor of leaded phosphor-bronze in the partially superconductive state at 2.2°K where the temperature coefficient of resistance was 0.17 deg^{-1}. The measurements include a frequency range of from 200 to 4000 cps.

A non-optimized phosphor-bronze bolometer, suitable for millimeter wave or infrared detection, was constructed and tested. The time constant was measured and found to be 4×10^{-3} second. Measurements of its minimum detectable absorbed power, W_{min}, were masked by spurious "pickup" noise from the chopper motor. An estimated value for W_{min}, calculated from the measured thermal conductance, etc., of the bolometer, and the noise factor of the amplifier system, was 1×10^{-10} watts at about 250 cps.

The experiments indicate that this figure could be improved upon, perhaps by two orders of magnitude, by optimizing the design, and yet the small time constant of 4×10^{-3} second could be maintained.

Further experiments on this type of bolometer are clearly desirable.

Considerable current noise was observed in a tantalum wire when it was maintained in the intermediate superconducting state at 4.2°K by means of a small magnetic field. The current noise power was proportional to the square of the dc biasing current, i^2, and appeared to be largely independent of frequency up to 5000 cps. In our first series of experiments, as reported in Technical Report No. 1, the ratio (n - 1) of the current noise power to the Johnson noise power was found to be:

$$(n - 1)/ i^2 = 15 \ (ma)^{-2}$$

In our second series of experiments on the current noise in a tantalum wire in the intermediate state freely suspended in helium gas at one atmosphere pressure, we found that for the frequency range 250 to 750 cycles per second

$$(n - 1)/i^2 = 6 \ (ma)^{-2}$$

and we found that for quasi-dc conditions, i.e. for a frequency of about one-half, with the helium gas around the specimen at atmospheric pressure,

$$(n - 1)/i^2 = 6 \times 10^{10} \text{ (ma)}^{-2}$$

A series of experiments were performed in which the tantalum wire was made part of an ac bridge, in order to find out whether the current noise was due to temperature fluctuations of the specimen as a whole. These measurements were not completed, owing to the early termination of the project, and consequently no definite conclusions have been drawn regarding the origins of the current noise.

Further experiments must be carried out to determine without doubt the fundamental causes of this observed current noise in tantalum.

It is concluded that if the observed current noise is due to temperature fluctuations, then tantalum in the intermediate state will form a bolometer material par excellence.

If on the other hand, as is discussed in this report, the observed current noise is due to some secondary processes associated with the impurities present in the tantalum, then further investigations should be made using other substances, such as tin for example, which can be prepared in a high state of purity and which would offer in principle the same advantages when employed as a low temperature bolometer.

The general conclusion, therefore, is that the work undertaken under this project has shown that low temperature bolometers must be seriously considered when discussing thermal detectors for maximum signal-to-noise values, and the merits of various bolometric materials, such as leaded phosphor-bronze and tantalum, have been studied. However, the study was not completed, and its results present problems of considerable future interest both in the fundamental physics involved and from the point of view of the practical application of low-temperature bolometers.

Signature page
to

Final Technical Report
on

Contract N6onr22527

NOTE: In submitting this report it is understood that all provisions of the contract between The Foundation and the Cooperator and pertaining to publicity of subject matter will be rigidly observed.

Investigator..B. Kaplan............ Date.2/17/53

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Supervisor....J. G. Daunt...............Date.2/14/53

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For The Ohio State University Research Foundation

Executive Director..Oram C. Woolpert RH...Date.2/16/53

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